STUDIES ON INSTABILITIES IN LONG-BASELINE TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER (TWSTFT) INCLUDING A TROPOSPHERE DELAY MODEL

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Abstract

Two-way satellite time and frequency transfer (TWSTFT) is one of the leading techniques for remote comparisons of atomic frequency standards. Frequencies can be compared with an uncertainty in the 10^{-15} range at an averaging time of 1 day, and time scale differences can be compared at the nanosecond level. These achievements are due to the fact that many delay variations of the transmitted signals cancel out in TWSTFT because of the reciprocity of the propagation path. However, reciprocity is not completely fulfilled. Especially, on long baselines, phase variations with amplitudes of 1 ns and more seem to limit the time and frequency transfer uncertainty. Following previous studies, we report on the progress of examining the TWSTFT link between Asia and Europe. We continue studies on the impact of the environmental temperature, the satellite motion, and the ionosphere on the phase variations. For the first time, a quantitative estimation of the differential troposphere delay for TWSTFT in the Ku-band is provided. Although all investigated candidates have indeed an impact on the measurement stability (from a few picoseconds caused by the troposphere to a few hundreds of picoseconds caused by the satellite motion), the overall observed effect is not completely understood at present. In summary, we estimate the individual contributions to the total measurement uncertainty.

INTRODUCTION

Two-way satellite time and frequency transfer (TWSTFT) is one of the leading techniques for remote comparisons of atomic frequency standards. Frequencies can be compared with an uncertainty in the

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10^{-15} range at an averaging time of 1 day **[1]**, and time scale differences can be compared at the nanosecond level **[2]**. The main advantage of the two-way technique is that undetermined delays on the signal path cancel in first order because of the path reciprocity of the transmitted signals. In the worldwide network maintained for the realization of International Atomic Time (TAI), TWSTFT is the preferably used method, with increasing importance as new ground stations at timing laboratories join the operational worldwide network **[3]**. Recently, the long baseline links between Asia and Europe became important for cesium fountain clock comparisons. It is well known and already observed that, especially on long baseline TWSTFT, the path delay reciprocity is not completely fulfilled. This is due to: (1) the different signal paths through different electronic components in the ground stations and generally in the satellite; and (2) the different frequencies used for up- and downlink to and from the satellite. For the Asia-Europe link via the geostationary (GEO) satellite IS-4, we use Ku-band frequencies of: 14.42625 GHz (uplink PTB), 11.465 GHz (downlink PTB), 14.265 GHz (uplink NICT, KRISS), and 12.67825 GHz (downlink NICT, KRISS). Daily phase variations, the so-called diurnals, of 1 ns and more have been observed regularly, and they are limiting the performance for frequency transfer at present. A number of possible reasons for such instabilities have been identified, such as the following ones (for an illustration, see Fig. 1):

- Atmospheric effects
  - Troposphere
  - Ionosphere
- Satellite motion
  - Sagnac effect
  - Path delay difference
- Environmental conditions
  - Ground station's internal delays affected by temperature, humidity, pressure
  - Satellite transponder delays affected by heating due to solar radiation.

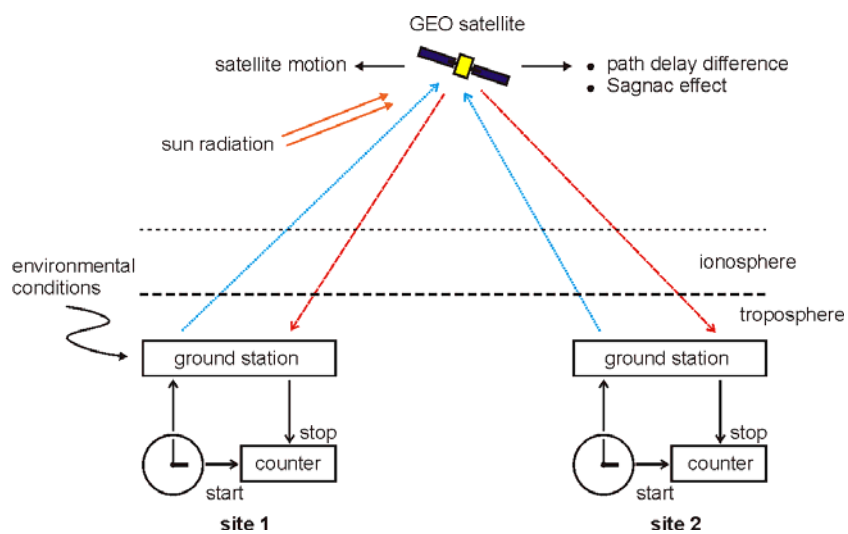


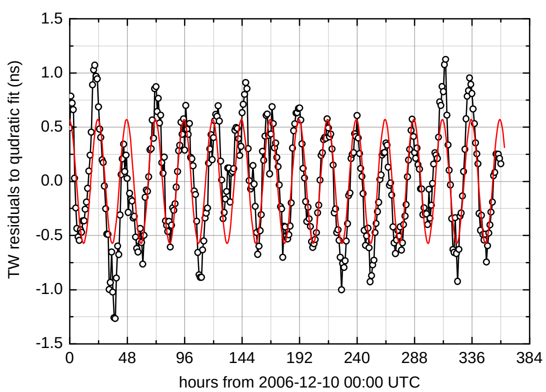
Fig. 1. Schematic of the possible sources of instabilities on a TWSTFT link between two sites.

In this report, we discuss these effects in particular for the TWSTFT links between Asia and Europe, which are in routine operation so far, i.e. the links between the National Institute of Information and Communications Technology (NICT) in Tokyo, Japan, and the Korea Research Institute of Standards and

Science (KRISS), Daejeon, connected to the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany **[5]**. After a phenomenological estimation of the magnitude of the observed diurnal effect in the following section, the above-listed effects are discussed in the subsequent sections. The results will be discussed in terms of the time deviation (TDEV). Parts of the phenomena were already investigated in previous studies **[6,7]** and the results will be compared (if applicable) with the newer results presented here. As an aside, we point to the well known fact that the TDEV statistic is sensitive to the data density **[6]**, so one has to be careful when comparing results with different data densities. In this study, we consistently use hourly data for the estimation of the magnitude of effects. We conclude with a summary of the results achieved and an outlook to future work necessary.

ESTIMATION OF THE DIURNAL COMPONENT

First, we characterize the amplitude of the diurnal component by selecting an exemplary period of TWSTFT measurements between NICT and PTB. We chose the hydrogen maser comparison in late 2006, when primary Cs-fountains in both labs were operated in parallel **[5]**. During a 15-day-interval, one TWSTFT measurement per hour was recorded; for more details, see **[5]**. From the raw clock comparison data as displayed in Fig. 2 (left), frequency and drift were removed (open black dots). Thereafter, a sinusoidal function (red line) was fitted to the data. Period, phase, and amplitude were free fit parameters. The results for periodicity and peak-to-peak amplitude are 23.98 h ± 0.03 h and 1.145 ns ± 0.039 ns, respectively. In the right graph of Fig. 2, the residuals from the subtraction of the sinusoidal fit function and the TWSTFT data are shown.



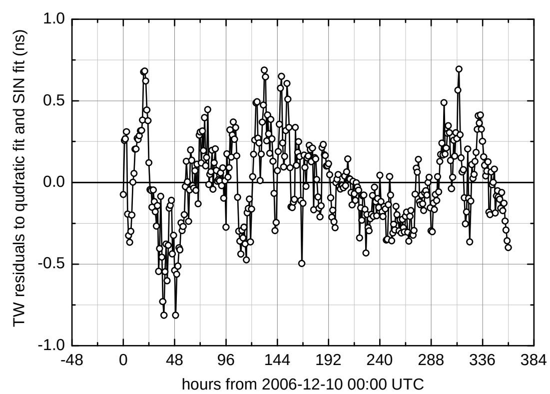


Fig. 2. Diurnal amplitude estimation: sinusoidal fit to hydrogen maser comparison data after removing frequency and drift in a 15-day-period starting on 2006-12-10 0:00 UTC (left), and residuals after removing the diurnal component (right).

In the investigated 15-day-period, the diurnal component could be very effectively removed from the time transfer data by fitting a sinusoidal function with constant amplitude. This can be clearly seen from the TDEV characteristic (see Fig. 3), too. The gray triangles show clear maxima at odd-numbered multiples of a half day. These correspond exactly with the shape of the TDEV plot for the sinusoidal fit (red circles). Both reach a TDEV of about 460 ps at maximum. The TDEV shape of the residuals (as depicted in Fig. 2, right hand) is almost flat at a level around 140 ps, and the noise type corresponds to flicker phase noise.

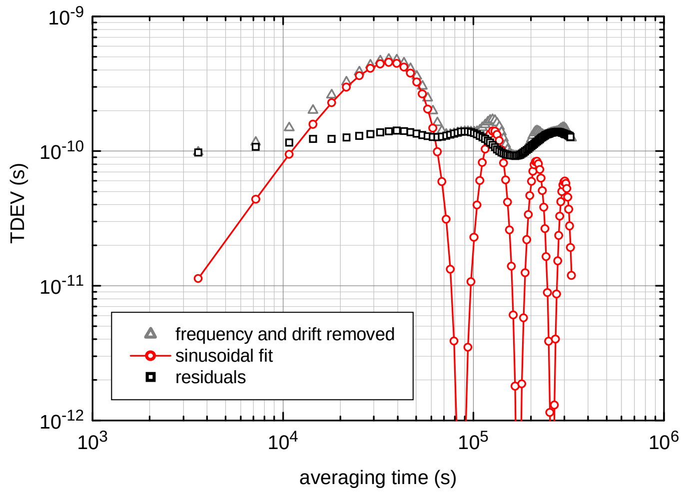


Fig. 3. Time Deviation (TDEV) statistics from the data displayed in Fig. 2.

TROPOSPHERE

The influence of the troposphere on TWSTFT measurements is usually assumed to be not frequency dependent **[8]**. But, in principle, the refractivity of the troposphere does have a frequency dependence, even at Ku-band frequencies. In 1989, Jespersen estimated the influence of the dispersive refractivity to be smaller than 0.5 ns **[9]**, and thus to be negligibly small compared with other effects of instability in these days' TWSTFT performance. However, as the precision reached the sub-nanosecond level in today's operational TWSTFT, the tropospheric delay should be considered as a candidate to cause non-reciprocities along the signal path. At least in future developments, e.g. employing the carrier phase in TWSTFT, sub-ps level in time transfer and 10^{-17} for frequency transfer at a 1-day averaging time have been predicted **[10]**), and the impact of the troposphere has to be taken into account.

For computing the impact of the troposphere dispersive refractivity, we apply Liebe's "Atmospheric Millimeter-Wave Propagation Model" **[11]**, which was originally designed – as stated in the title – for millimeter wavelengths for radar applications, but whose model predictions are in good agreement with experimental data down to 2.5 GHz **[12]**, and thus covering Ku-band frequencies as they are used for the TWSTFT links. In Fig. 4, a flow chart of the implementation of Liebe's model into the delay difference computation is depicted. From his model, we took the dispersive parts of the local line absorption, non-resonant dry air spectrum, and the water vapor continuum to compute the dispersive complex refractivity (N) and group delay (τ) expressed in units of ps/km in dependence on frequency (f), temperature (T), relative humidity (U), and pressure (P). The group delay for frequencies up to 100 GHz for different relative humidity values is depicted in Fig. 5 (temperature and pressure is kept fixed at 10 °C and 1013 hPa, respectively). Two regions with absorption lines at 22 GHz and around 60 GHz are shown. Overall, 43 absorption lines for O_2 and 29 for H_2O below 1000 GHz were implemented in Liebe's model. Most of them contribute only with their low-frequency tail to τ. In a further step, the delay difference ($d\tau$) between up- and downlink at the two corresponding different radio frequencies is computed.

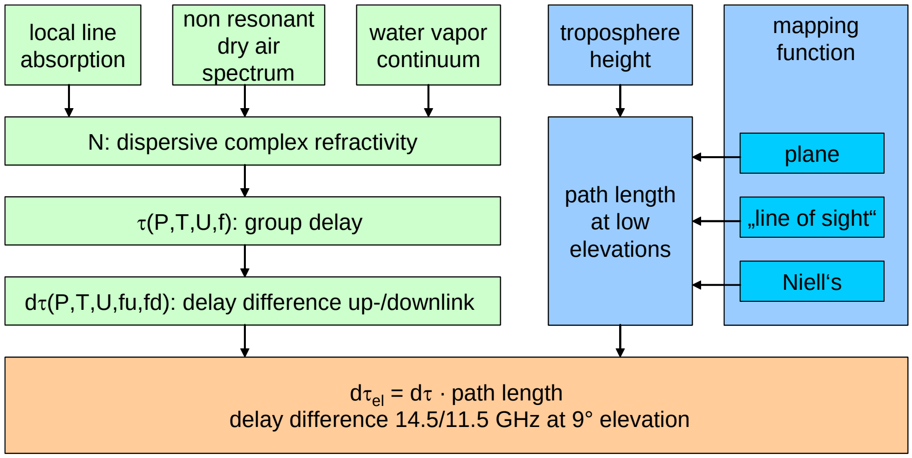


Fig. 4. Flow chart of the model to compute the non-reciprocity in Ku-band TWSTFT due to tropospheric delay.

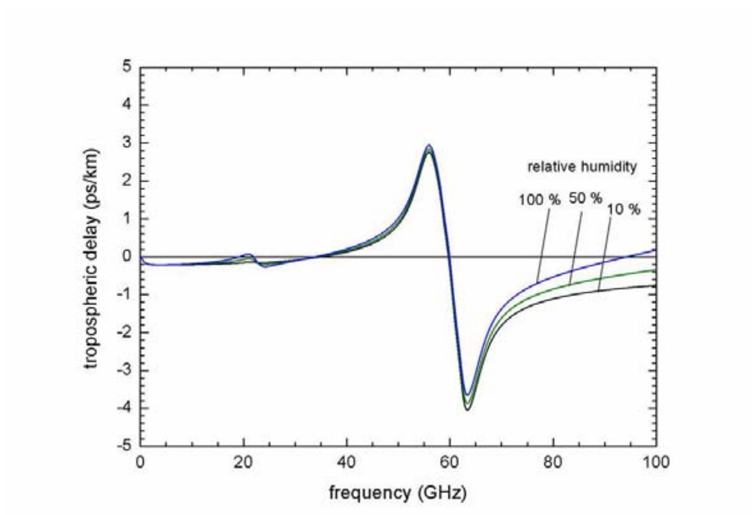


Fig. 5. Troposphere group delay (τ) in dependence of frequency, the result of applying Liebe's model.

Once the group delay difference is computed, the path length trough the troposphere has to be determined by applying a suitable geometrical model. Two input parameters are needed: The height of the troposphere and a mapping function to describe the path of the radio signal. We presume a homogenous troposphere and neglect higher-order dispersive effects on the signal path. The height is computed from equation (7.23) in Kaplan's book **[13]**, giving an estimation for the wet layer height. Input parameters are temperature, pressure, and dispersive refractivity. The latter was used from Liebe's model instead of the phenomenological approach described in Kaplan's book. The result is shown in Fig. 6 (left). The height varies in a range from 10 km to 12 km for a wide temperature range. On the other hand, humidity and pressure have only a negligible influence.

For elevation angles below 90°, a mapping function has to be applied to describe the real path length. This is a crucial point, because on long-baseline links (accompanied by low elevation angles), the path length through the troposphere can be ten times larger than the zenith path length at 90°. For our link, the elevation angles are as follows: 8.4° (PTB), 9.6° (NICT), and 19.0° (KRISS). We tried three different

mapping functions. Two are rough approaches, namely a simple plane troposphere (assuming a flat Earth) and the straight "line of sight" through the spherical troposphere shell **[14]**. While these two functions result in too large or too small values, respectively, we use for the path length computation the mapping function as reported by Niell (equation 4 in **[15]**). The results for all three mapping functions for different elevation angles at a fixed troposphere height (11 km) is shown in Fig. 6 (right).

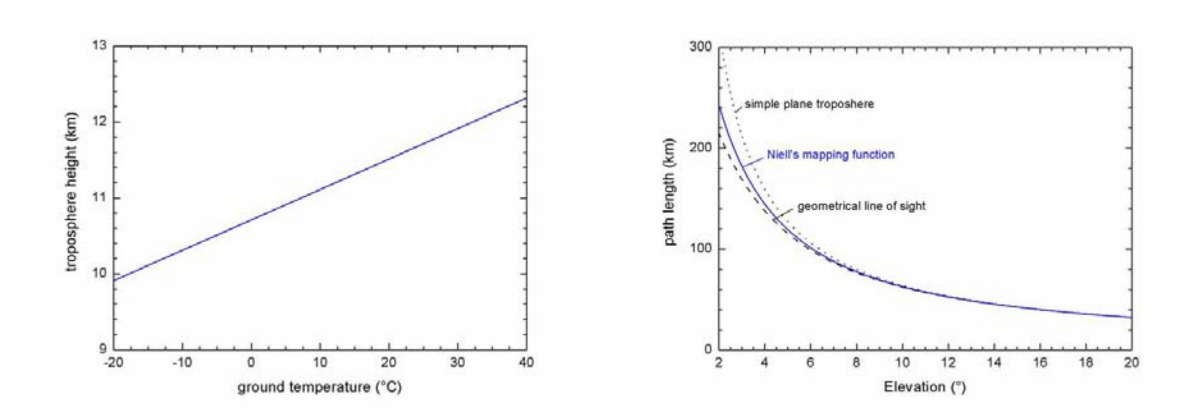


Fig. 6. Geometry of the troposphere. Left: height in dependence of ground temperature, presure and humidity influence is negligible. Right: path length using different mapping functions.

The overall delay difference between up- and downlink from one ground station to the satellite ($d\tau_{el}$) is computed from multiplication of the delay difference per length ($d\tau$) with the path length. In Fig. 7 (left), the overall differential delay between up- and downlink from PTB's ground station to IS-4 is depicted. The largest variations are due to temperature and humidity. Pressure would cause variations of < 0.1 ps, only. The effective tropospheric delay for the whole link, e.g. between NICT and PTB, can then be computed using environmental data records (temperature, humidity, pressure) from both ground station locations. The resulting delay is shown in Fig. 7 (right) for 300 days in 2007. Indeed, there is an overall delay, varying in dependence of the environmental conditions. However, the variations are rather small (peak-to-peak: 4 ps), compared with other effects, and with the actual stability of TWSTFT measurements. The TDEV analysis (see Fig. 8) reveals instabilities well below the ps level (< 0.3 ps). Thus, the troposphere can be safely neglected for today's TWSTFT link performances. Nevertheless, if the full potential of TWSTFT using the carrier phase is tapped, the troposphere has to be reconsidered.

IONOSPHERE

The TWSTFT performance impact of the ionosphere was investigated previously. Based on IGS TEC maps, Parker and Zhang **[6]** predict delay variations with a strong diurnal component of up to 300 ps and a corresponding maximum TDEV value of 40 ps at a ½-day averaging time for the link between NIST and PTB. For the link between NICT and PTB, the ionospheric delays were computed for 6 days starting from 2006-02-01 using the Global Ionosphere Map (GIM) published by the Center for Orbit Determination in Europe (see **[7]** and references therein). GIM provides updated data every 2 hours, which were interpolated to fit to the hourly TWSTFT measurements. During that study period, peak-to-peak variations of less than 150 ps were found. The results in terms of TDEV are shown in Fig. 9. The maximum reaches 30 ps at a ½-day averaging time. Because the ionosphere delay depends not only on time of day, but also on the season, as well as the stations' position, one can expect significant differences in both studies.

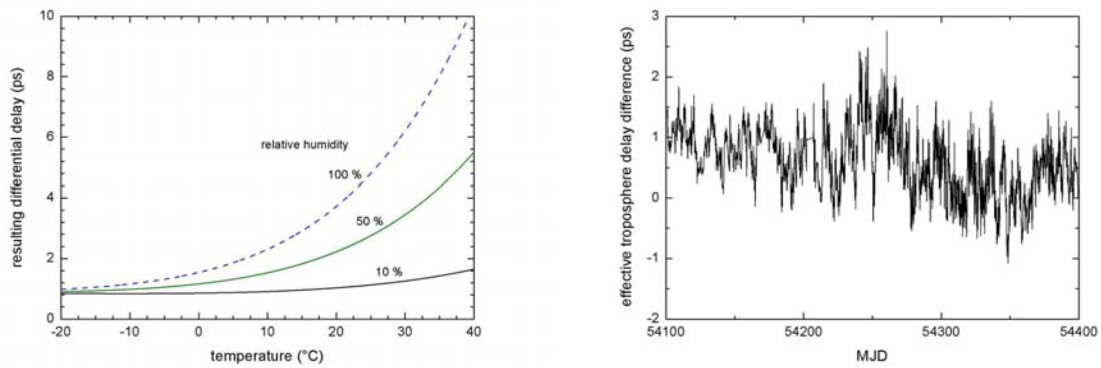


Fig. 7. Troposphere delay variations in dependence of temperature and humidity (left) for the connection from PTB's ground station to the GEO IS-4 and effective troposphere delay for the link between NICT and PTB over a 300-day period (right). MJD 54100 corresponds to 2006-12-31.

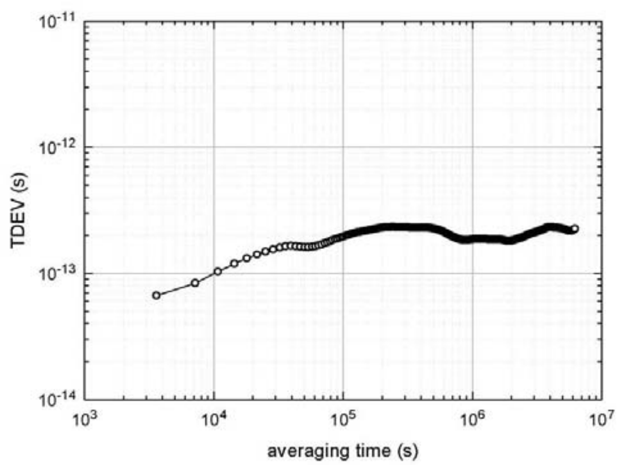


Fig. 8. TDEV of the data depicted in Fig. 7 (right).

SATELLITE MOTION

It is common understanding that the position of a GEO satellite is fixed with respect to the Earth and, hence, to the ground stations. However, a small motion of the satellite around the nominal center position happens. This motion is mainly due to the sun's gravitational potential and the satellite positioning adjustment from the control stations of the satellite operator. This motion causes a variation of the Sagnac effect and a variation of the path delay difference between the signals transmitted from both ground stations to the satellite. In the following, both effects will be briefly discussed.

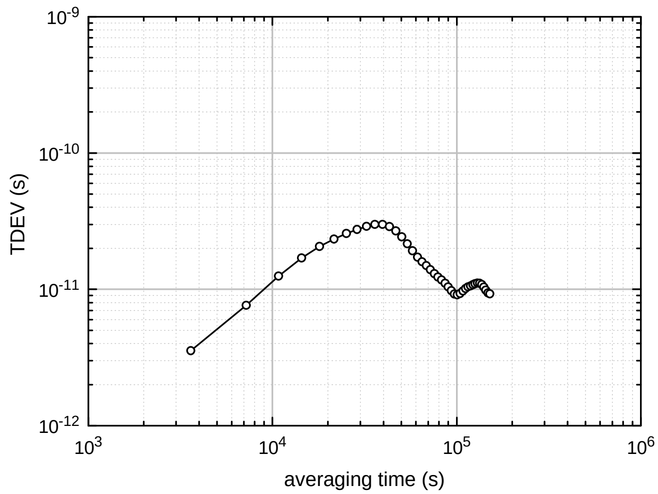


Fig. 9. TDEV plot of the ionosphere delay variations on the link between NICT and PTB, as computed in Ref. **[7]**.

Sagnac Effect

In operational TWSTFT, both ground stations and the satellite spin around the rotation axis of the Earth. For true time transfer, i.e. during dedicated calibration campaigns **[2]**, one has to account for the Sagnac effect by applying appropriate corrections **[8]**. Such corrections can be of the order of 100 ns. But only as long as the satellite position is assumed to be fixed, the Sagnac correction is fixed, too. The actual motion of the satellite IS-4 was computed from two line elements as published by the North American Aerospace Defense Command (NORAD) (see **[7]** and references therein). In Fig. 10 (left), the Sagnac delay between NICT and PTB via IS-4 is shown. It is computed for two different periods, in February 2006 (as reported in **[7]**) and June 2007. Two different peak-to-peak amplitudes were observed, 650 ps and 50 ps, respectively. At a ½-day averaging time, the corresponding TDEV statistics have maxima of

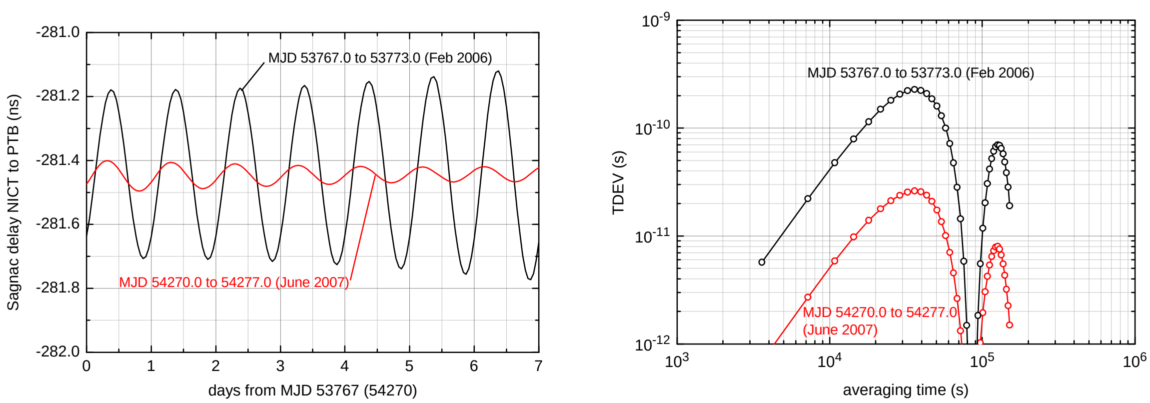


Fig. 10. Sagnac effect impact (left) and corresponding TDEV statistics (right) of TWSTFT measurements between NICT and PTB for two periods: 7 days in February 2006 and June 2007.

250 ps and 25 ps, respectively. The rather high difference in amplitude and phase of the diurnal component is not understood at present. It may be due to different satellite position control modes in both periods.

PATH DELAY DIFFERENCE

The motion of the satellite relative to the Earth's surface causes a varying path length between the satellite and the two ground stations during TWSTFT sessions. Because the distances of the two stations from the satellite are not the same, the signals transmitted from the stations do not reach the satellite at the same epoch. E.g., for the link NICT-PTB via IS-4, the signal from NICT arrives 0.4 ms earlier than that from PTB. For the link KRISS-PTB, the KRISS signal arrives about 3.7 ms earlier. At the same time, the satellite velocity causes changes in the overall path length and, thus, the path delay in TWSTFT does not cancel completely. The estimation of the effect requires that ranging data are available in parallel to the regular TWSTFT data. The transponder configuration on IS-4 was temporarily changed so that such data could be taken (see **[7]** for details).

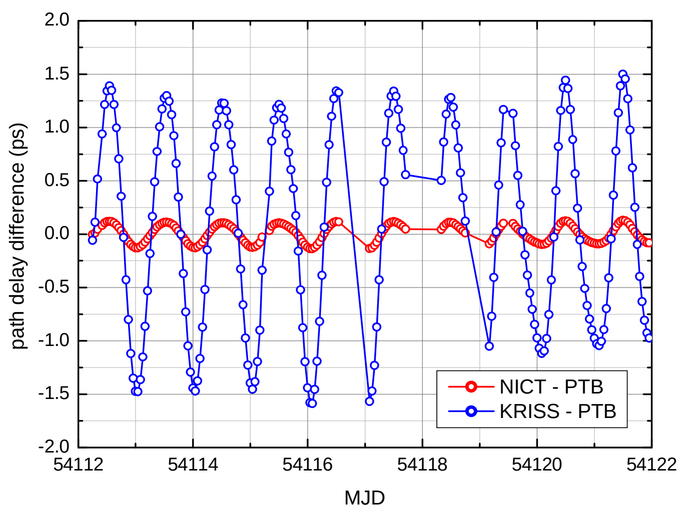


Fig. 11. Path delay difference in TWSTFT due to satellite motion.

The path delay differences cause non-reciprocities in for the links between NICT and PTB and between KRISS and PTB of peak-to-peak (TDEV) 0.3 ps (0.1 ps) and 3 ps (1.1 ps), respectively. Parker and Zhang **[6]** found values for transatlantic TWSTFT links via the GEO satellite IS-707 in a range from 14 ps to 30 ps.

ENVIRONMENTAL CONDITIONS

The impact of environmental parameters, such as temperature and humidity, surely play an important role regarding the limiting factors of TWSTFT performance. Investigations were done to characterize single components of ground stations [**6**], and assuming a ground station temperature sensitivity of 10 ps/K, TDEV values < 100 ps were predicted (see **[6]** and references therein). In the same work, a first approach to characterize the humidity impact was done: 10 ps in terms of TDEV (with a station sensitivity of 1 ps per percent of relative humidity). We studied the correlation between outdoor environmental parameters

and observed delay variations on TWSTFT links [**7**]. Until now, no clear picture is available to model or to better understand and control the delay variations. In this work, we only add one aspect of a possible temperature impact on the ground stations. We discuss if there is a correlation between the daily mean temperature and the diurnal amplitude. This would give us a hint if the ground stations' temperature coefficients may depend on the seasonal variation of daily averaged temperature. Because two ground stations (at NICT and PTB) are involved, we correlate the diurnal amplitude to the temperature at PTB alone, NICT alone, PTB – NICT, and PTB + NICT. These four temperature runs are depicted in Fig. 12 (left, upper graph) for the period winter/spring 2007. For the same period, the diurnal amplitude is shown (lower graph). In Fig 12, right part, the correlation between the diurnal amplitude and PTB outdoor daily mean temperature is depicted. The overall correlation coefficient is -0.36 (the other correlation coefficients are -0.20, -0.18, -0.32, respectively). The red lines in the right graph highlight that there may be a temperature-independent diurnal component (straight line) and a temperature-dependent component below < 10 °C (dashed line). At the present stage of our investigations, we hesitate to estimate the overall temperature effect, but it might be significantly higher than estimated by Parker and Zhang [**6**]. In ongoing work, ground station delay variations obtained by employing the satellite simulator technique are compared with environmental temperature **[16]**. This may provide useful information to deepen the understanding of the ground station stability.

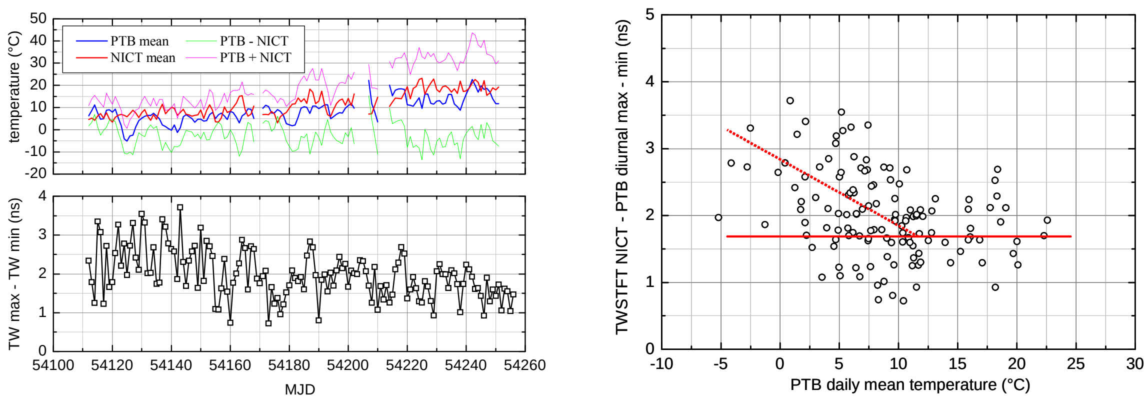


Fig. 12. Correlation between outdoor temperature and diurnal variations on TWSTFT measurements between NICT and PTB.

There is one component along the signal path which has not been discussed until now. The satellite used for intercontinental TWSTFT usually employs two different transponder configurations for the link from Asia to Europe and vice versa. Thus, temperature changes and temperature gradients may cause delay changes in the satellite which differ for the two signals. The exposure of the satellite to the sun can cause a stable diurnal component whose amplitude, however, is unknown. At present, no data regarding the satellites' internal temperatures are available, and nothing is known about the differential transponder delay versus temperature. Actually, that could constitute an important part of the whole effect.

CONCLUSION

We have studied possible origins of diurnal components in TWSTFT between Asia and Europe connecting NICT and KRISS with PTB. The results achieved are summarized in Table 1. The diurnal component for the link between Asia and Europe is estimated to 460 ps in terms of TDEV. To our

knowledge, all accessible and conceivable mechanisms were studied, but at present they cannot explain the observed amplitude of actual diurnals. The candidates in descending order of impact are the Sagnac effect change due to satellite motion, environmental temperature, ionosphere, humidity, and path delay difference due to satellite motion, and troposphere.

Table 1. Summary of the estimated instabilities in TWSTFT: estimated amplitudes (peak-to-peak) and TDEV statistics.

Instability	**This work**		**Parker and Zhang [6]**	
	amplitude (ps)	**TDEV (ps)**	**Amplitude (ps)**	**TDEV (ps)**
diurnal component	1100	460		
Residual	~500	140		
troposphere	< 4	< 0.3		
ionosphere	150	30	300	40
Sagnac effect	50 – 650	25 - 250		
Path delay difference	0.3 – 3	0.1 – 1.1		< 15
Temperature				< 100
humidity				10

Future work should consist of further detailed studies on the environmental parameter impact, the Sagnac delay, and, if possible, the satellite transponder delay. Study of the latter needs, however, the support of the satellite operator.

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REFERENCES

[1] A. Bauch, J. Achkar, S. Bize, D. Calonico, R. Dach, R. Hlavać, L. Lorini, T. Parker, G. Petit, D. Piester, K. Szymaniec, and P. Uhrich, 2006, *"Comparison between frequency standards in Europe and the US at the 10^{-15} uncertainty level,"* **Metrologia, 43,** 109-120.

[2] D. Piester, A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, and O. Koudelka, 2008, *"Time transfer with nanosecond accuracy for the realization of International Atomic Time,"* submitted to **Metrologia.**

[3] E. F. Arias, W. Lewandowski, and Z. Jiang, 2007, *"BIPM report on TAI/UTC computation,"* presented at the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 26-29 November 2007, Long Beach, California, USA, but not submitted for publication.

[4] M. Fujieda, T. Gotoh, D. Piester, M. Kumagai, S. Weyers, A. Bauch, R. Wynands, and M. Hosokawa, 2007, *"First comparison of primary frequency standards between Europe and Asia,"* in Proceedings of TimeNav'07, the 21st European Frequency and Time Forum (EFTF) Joint with 2007 IEEE

International Frequency Control Symposium (IEEE-FCS), 29 May-1 June 2007, Geneva, Switzerland (IEEE Publication CH37839), pp. 937-941.

[5] H. Maeno, M. Fujieda, D. Piester, A. Bauch, M. Aida, Q. T. Lam, T. Gotoh, and Y. Takahashi, 2006, *"Establishment of a TWSTFT link between Asia and Europe connecting NICT and PTB,"* in Proceedings of the 20th European Frequency and Time Forum (EFTF), 27-30 March 2006, Braunschweig, Germany, pp. 575-579

[6] T. E. Parker and V. Zhang, 2005, *"Sources of Instability in Two-Way Satellite Time Transfer,"* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and the 37th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE Publication 05CH37664C), pp. 745-751.

[7] M. Fujieda, T. Gotoh, M. Aida, J. Amagai, H. Maeno, D. Piester, A. Bauch, and S. H. Yang, 2007, *"Long baseline TWSTFT between Asia and Europe,"* in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI), 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 499-510

[8] ITU-R Recommendation TF.1153-2, 2003, *"The operational use of two-way satellite time and frequency transfer employing PN codes"* (ITU-R, Geneva, Switzerland).

[9] J. Jespersen, 1989, *"Impact of atmospheric non-reciprocity on satellite two-way time transfers,"* in Proceedings of the 43rd Annual Frequency Control Symposium, 31 May-2 June 1989, Denver, Colorado, USA (IEEE Publication 89CH2690-6), pp. 186-192.

[10] M. Imae, 2006, *"Review of Two-Way Satellite Time and Frequency Transfer,"* **MĀPAN – Journal of Metrology Society of India**, **21**, 243-248.

[11] H. J. Liebe, 1989, *"MPM – An Atmospheric Millimeter-Wave Propagation Model,"* **International Journal of Infrared and Millimeter Waves**, **10**, 631-650.

[12] H. J. Liebe, 1985, *"An updated model for millimeter wave propagation in moist air,"* **Radio Science**, **20**, 1069-1089.

[13] J. L. Leva, M. U. de Haag, and K. Van Dyke, 1996, *"Performance of Standalone GPS,"* in **Understanding GPS: Principles and Applications** (ed. E. D. Kaplan; Artech House, Boston), pp. 237-320.

[14] J. J. Spilker, 1996, *"Tropospheric Effects on GPS"*, in **Global Positioning System: Theory and Applications, Vol. 1** (ed. B. W. Parkinson and J. J. Spilker; American Institute of Aeronautics and Astronautics, Washington, D.C.), pp. 517-546.

[15] A. E. Niell, 1996, *"Global mapping functions for the atmosphere delay at radio wavelengths,"* **Journal of Geophysical Research**, **101**, No. B2, 3227-3246.

[16] W. H. Tseng, H. T. Lin, P. C. Chang, S. Y. Lin, and K. M. Feng, 2008, *"Analysis of Delay Fluctuations in Two-WayTtime Transfer Earth Stations,"* in Proceedings of the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 26-29 November 2007, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 541-550.